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TECHNICAL NOTE 3446

EFFECT OF AMMONIA ADDITION ON LIMITS OF FLAME
PROPAGATION FOR ISOCTANE-AIR MIXTURES
AT REDUCED PRESSURES AND
ELEVATED TEMPERATURES

By Cleveland O'Neal, Jr.

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Cleveland, Ohio



Washington

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AIR MIXTURES AT REDUCED PRESSURES AND ELEVATED TEMPERATURES

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SUMMARY

Pressure limits of flame propagation were determined for isooctane, ammonia, and mixtures of the two in air at several temperatures in the range of 60° to 400° C. A hot-wire ignition source was employed and the 2-inch-diameter flame tube was closed at both ends. Two-lobed pressure-limit curves were obtained for all mixtures except ammonia in air.

For all mixtures studied, the rich limit rose considerably and the lean limit decreased slightly, resulting in a broadening of the flammable region, when temperature was raised. The minimum pressure limit was decreased by raising the temperature.

Addition of ammonia broadened the flammable region considerably up to about an ammonia-air weight ratio of 0.02, but thereafter the region narrowed. Over the range of ammonia-air ratios studied (zero to 0.039), the lean limit increased but very little and was in fair agreement with values predicted from Le Chatelier's mixture rule. On the other hand, rich limit equivalence ratio maximized at an ammonia-air ratio of about 0.02 which is not predicted by Le Chatelier's rule. The lowest value of the minimum pressure was also found at an ammonia-air ratio of about 0.02.

Gas-analysis data for ammonia after passage of flame in the ternary mixtures showed all the additive was consumed in lean mixtures and from 48 to 62 percent was used in the rich mixtures.

INTRODUCTION

In a turbojet engine, additional thrust may be obtained by injecting a suitable coolant into the compressor; ammonia and water have been employed for this purpose (ref. 1). Since ammonia is itself a fuel, it is desirable to determine how its presence will affect combustion. Some insight may be gained by studying the fundamental combustion properties of the ammonia when used alone and when combined with a typical fuel.

A convenient property to investigate is the pressure limit of flame propagation from which concentration limits may be derived. A rich and a lean concentration limit of a particular fuel bound an area, which may be termed the "flammable region". This region of flame propagation has been found to widen when temperature is raised for methane (refs. 2 and 3) and pentane (ref. 4), and the broadening of the region is brought about by a decrease in the lean limit and an increase in the rich limit. For the higher hydrocarbons, only the variation of the lean limit with temperature has been investigated (ref. 5). In addition to studying the ammonia effect on the limits of isooctane in air, the temperature effect was also determined.

In this report, pressure limits were measured at reduced pressures (up to 400 mm Hg) for isooctane, ammonia, and mixtures of the two in air at several temperatures in the range of 60° to 400° C. The work was performed in a pyrex glass tube of standard dimensions (2-in. I. D. and 4-ft long) closed at both ends (ref. 6). A hot wire was used as the ignition source and propagation was upward. Gaseous ammonia with ammonia-air ratios of 0.020 and 0.039 by weight was added to the isooctane-air mixtures. Data showing the amount of ammonia consumed after passage of flame through rich and lean mixtures containing isooctane and ammonia are presented.

Pressure-limit curves showing a plot of the pressure limit against equivalence ratio are presented for isooctane at five temperatures and for ammonia at two temperatures. Similar plots are shown for each of the ternary mixtures at five temperatures. These pressure-limit - equivalence-ratio plots were obtained by cross-plotting pressure-limit and temperature data at a constant temperature. Lean and rich concentration limits for isooctane-air at 400 millimeters of mercury are plotted against ammonia-air ratio to show the effect of added ammonia on the flammable region; these limits are then plotted against temperature to obtain the temperature effect. The mixture rule of Le Chatelier was employed and concentration limits of flame propagation were calculated at three temperatures for the ternary mixtures and compared with observed values.

EXPERIMENTAL DETAILS

Apparatus

A diagram of the apparatus used in this investigation is shown in figure 1. Reduced-pressure limits of flame propagation were determined in a pyrex glass tube (4-ft long and 2-in. I. D.), which was enclosed in a resistance-wound furnace with three separate windings. The flame was observed through a 1/2-inch slit in the furnace.

Mixture Preparation

The mixture storage tank with a sealed-in, vaned-type stirrer, the fuel capsule, the air inlet, and a precision manometer were mounted within a glass-walled tank containing mineral oil which served as a constant-temperature bath. The bath was maintained at a temperature of approximately 65° C throughout the investigation to ensure complete vaporization of the isooctane.

The composition of the mixtures to be tested was determined from the partial pressures of the constituent gases. A vacuum pump together with a cold trap in acetone and dry ice was used to evacuate the system to a pressure of less than 0.1 millimeter measured with a McLeod gage. Following evacuation of the storage tank, isooctane was allowed to evaporate into it to the desired pressure. With the partial pressure of isooctane recorded, air from which carbon dioxide and water had been removed by Ascarite and Anhydrone, respectively, was admitted into the tank until the desired total pressure was attained. All pressure readings from the manometer were obtained by means of a cathetometer accurate to approximately 0.05 millimeter. The mixture was stirred for 4 or 5 minutes to ensure homogeneity. Subsequent fuel concentrations were obtained by successive dilutions with air. For the mixtures containing ammonia, the same procedure was employed except that the additive was admitted following evaporation of the hydrocarbon.

Temperature Measurements

For the purpose of obtaining adequate temperature measurements, the 4-foot tube was divided by marking the furnace into three zones corresponding to the furnace windings, the top and bottom zones being $\frac{3}{4}$ of a foot and the middle portion $2\frac{1}{2}$ feet. Five readings were recorded in the $2\frac{1}{2}$ -foot section and two readings were taken in each of the terminal sections by means of a thermocouple and potentiometer. The thermocouple was moved from station to station inside the tube. Average temperatures were obtained for each of the three sections, and these values were then averaged to obtain a mean experimental temperature. Individual measurements within a section deviated from the mean by $\pm 5^{\circ}$ C, and sectional temperatures differed by no more than $\pm 10^{\circ}$ C. Temperature measurements were recorded before and after each pressure-limit determination to detect any variation that might have occurred during a single run. No appreciable difference in the two temperatures was observed.

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Pressure Measurements

In order to determine the pressure limit, the combustible mixture to be tested was run into the flame tube to a desired pressure. The mixture was then ignited at the lower end of the flame tube by means of a hot wire consisting of 10 or 12 inches of 24-gage (B and S) Nichrome wire wound in the form of a helix. The ends of the coil were attached to conducting rods fastened in the bottom of a removable glass-ignition unit. A watt meter and a timer were used to obtain a record of the power and the length of time it was applied. A power of 90 watts was applied for 3 to 6 seconds for all pressure limits determined except those for ammonia. For ammonia, 100 watts were necessary in the same time interval.

The lowest pressure that would support flame travel over the complete length of the tube for a given mixture was taken as the pressure limit (the conventional criterion for pressure limits, ref. 6). A propagating and a nonpropagating pressure were determined by several trials until they were 4 millimeters apart. The midpoint between these two pressures was taken as the limit; thus, the data points shown herein were obtained with a precision of ± 2 millimeters. The deviation from one measurement to another with lean mixtures was ± 4 millimeters, and for rich mixtures ± 8 to 10 millimeters as indicated by check points shown in figure 2.

Complete pressure-limit - equivalence-ratio curves were determined for isooctane in air at 60° , 145° , 210° , 323° , and 395° C; and for ammonia in air at 62° and 335° C. Each curve at a single temperature was determined in the course of one day. With the ternary mixtures, the concentration was held constant and flame-tube temperature varied. Generally, pressure limits for a single mixture concentration were determined at four or five temperatures between 55° and 470° C in a single day. Data obtained in this manner were plotted as pressure limit against temperature. These lines were then cross-plotted at a constant temperature and concentration to obtain the pressure-equivalence ratio curves for the ternary mixtures. The highest pressure at which limits were determined was 400 millimeters of mercury.

Calculation of Equivalence Ratio

All fuel concentrations in this report are given in terms of the equivalence ratio (actual fuel-air ratio divided by stoichiometric fuel-air ratio) calculated on a volume basis. (The same values of equivalence ratio would have been obtained if calculations were made on a weight basis.) For ammonia, the combustion products were assumed to be nitrogen and water when calculating the stoichiometric fuel-air ratio. In the case of the ternary mixtures, it was necessary to calculate the fuel-air ratio at stoichiometric for each mixture tested. The actual ratio of fuel to air was given by

$$\left(\frac{f}{a}\right)_{\text{actual}} = \frac{P_{\text{C}_8\text{H}_{18}} + P_{\text{NH}_3}}{P_{\text{air}}} \quad (1)$$

where P is the partial pressure in millimeters of mercury. At stoichiometric, the fuel-air ratio was obtained from the following equation:

$$\left(\frac{f}{a}\right)_{\text{stoichiometric}} = \frac{P_{\text{C}_8\text{H}_{18}} + P_{\text{NH}_3}}{59.7P_{\text{C}_8\text{H}_{18}} + 3.58P_{\text{NH}_3}} \quad (2)$$

where 59.7 and 3.58 are the stoichiometric proportion of air for 1 millimeter of isooctane and ammonia, respectively. The equivalence ratio then becomes

$$\frac{\left(\frac{f}{a}\right)_{\text{actual}}}{\left(\frac{f}{a}\right)_{\text{stoichiometric}}} = 59.7 \frac{P_{\text{C}_8\text{H}_{18}}}{P_{\text{air}}} + 3.58 \frac{P_{\text{NH}_3}}{P_{\text{air}}} \quad (3)$$

Two concentrations of ammonia mixed with isooctane and air were employed in this investigation. Expressed as the weight ratio of ammonia to air, the concentrations were 0.020 and 0.039. With both ammonia-air ratios, some gas-analysis data for ammonia were obtained before and after passage of flame. A gas bulb of known volume was evacuated and then attached to an outlet from the flame tube with a tight-fitting rubber hose. The bulb was filled with the gaseous mixture, and boric acid was used to absorb the ammonia in the mixture. The resulting solution was titrated with standard solution of 0.02N hydrochloric acid. Samples were taken in duplicate for the analysis.

RESULTS AND DISCUSSION

In this section, the effect of equivalence ratio on pressure limits of flame propagation will be discussed first. Next, the influence of temperature on the concentration limits of flame propagation at 400 millimeters of mercury will be considered and, finally, the effect of added ammonia on isooctane concentration limits will be described. In this discussion the word "limit" will be used to refer to concentration limits of flame propagation at the experimental pressure of 400 millimeters of mercury. Whenever the pressure limit of flame propagation is discussed, it will be designated as such.

Effect of equivalence ratio on limits. - Pressure limits for isooctane-air mixtures as a function of equivalence ratio at a series of temperatures between 60° and 400° C are presented in figure 2; experimental data are tabulated in table I(a). Where comparison is possible, results are consistent with those obtained by others. For example, lean and rich limits for isooctane in air at 60° C (fig. 2(a)) are found at equivalence ratios of 0.6 and 3.8; under comparable conditions other workers have reported 0.5 and 3.8 (ref. 6) and 0.5 and 3.6 (ref. 7).

Table I(b) shows pressure limits and equivalence ratios for ammonia in air at 62° and 335° C. Plots of these data are shown in figure 3. Ammonia-air limits at atmospheric pressure have been determined at 18° C (ref. 8) and at 26° C (ref. 9). These may be compared with those of the 62° C curve (fig. 3(a)), since limits are not greatly affected by a small temperature increase nor by a decrease in pressure below atmospheric for the first few hundred millimeters (ref. 6). The values reported in both references 8 and 9 for lean and rich limits in terms of equivalence ratio were 0.68 and 1.30, respectively; and from figure 3(a) the lean and rich limits are 0.60 and 1.50. This discrepancy probably arises from a difference in ignition source. Gun cotton was employed as an ignition source in references 8 and 9. It gave for hydrocarbons, at least, narrower limits than hot-wire ignition (ref. 10).

Inspection of the 60° and 62° C curves of figures 2(a) and 3(a) shows that isooctane has a much greater range of flame propagation than ammonia; isooctane having lean and rich limits of 0.57 and 3.85, and ammonia 0.60 and 1.50, respectively. The flammable region, that is, the rich minus the lean limit, for isooctane is 3.6 times that of ammonia.

Plots of pressure limits against equivalence ratio for the ternary mixtures at several temperatures were obtained by cross-plotting from pressure-limit - temperature curves derived from the data of table II. Figure 4 shows the pressure-limit - equivalence-ratio plot for mixtures having an ammonia-air ratio of 0.02; and figure 5 shows the same plots for an ammonia-air ratio of 0.039. The points on these curves, represented by a diagonal line, give some indication as to the spread in the cross-plot data. The same symbol is used in all succeeding curves in this report where cross-plotting is involved. (This symbol does not represent actual experimental data.)

Two-lobed pressure-limit curves, which are associated only with upward propagation (ref. 10), were observed for all mixtures containing isooctane. In some of the figures, lobes have been indicated by dashed lines. In this region, the flames appeared extremely rough and unstable, and reproducibility in general was very erratic. The second lobe appears to shift at the higher temperatures to greater equivalence ratios and higher pressures. For ammonia in air, smooth burning took place over the entire flammable region. No erratic behavior of the flame was observed and the two-lobe phenomenon is absent as can be seen in figure 3.

Effect of temperature on limits. - The flammable region of isooctane is widened on raising the temperature; the rich limit is increased and the lean limit is decreased. The lean and rich limits were obtained from the pressure-limit - equivalence-ratio curves of figure 2 at 400 millimeters and plotted against temperature in figure 6(a). Also plotted in this figure are some experimental data taken from reference 5; the agreement is very good.

A plot of lean and rich limits (taken from the pressure-limit - equivalence-ratio curves for ammonia, fig. 3) against temperature also shows a broadening of flammable region with increasing temperature. Because ammonia limits were determined at only two temperatures, data from reference 8 are also plotted in figure 6(b); a comparison of the slopes of the two lines at each limit (rich and lean) gives justification for drawing the straight line through the two experimental points. The seemingly wide variation in the two flammable regions may be caused by the difference in ignition source. As mentioned earlier, gun cotton was used as the ignition source in reference 8, and the data reported herein were obtained with a hot wire.

The plots of ternary mixtures with isooctane-air and added ammonia show the same trend with temperature as those for isooctane in air and ammonia in air. The plots are shown in figures 6(c) and (d) for ternary mixtures having an ammonia-air ratio of 0.020 and 0.039, respectively.

The lean limit in the series of plots in figures 6(a) to (d) decreases linearly as the temperature is raised, but the increase in the rich limit for isooctane and the ternary mixtures is nonlinear.

The minimum pressure limit, that is, the pressure at which the lean and rich limits coincide on a plot of pressure limit against equivalence ratio, is known to change with tube diameter (ref. 10). Figures 2 to 5 show that this factor decreases as the temperature is raised, although data are not sufficiently precise to permit quantitative examination of this trend.

Effect of added ammonia on limits. - The effect of added ammonia on the limits of isooctane at 400 millimeters of mercury pressure may be ascertained by plotting lean and rich limits at a specified temperature against the ammonia-air weight ratios employed in this investigation. Limits for isooctane and the two ternary mixtures were obtained from figures 2(a), (c), and (e), 4(a), (c), and (e), and 5(a), (c), and (e), respectively. These limits are plotted against ammonia-air ratio at 60°, 210°, and 395° C in figures 7(a), (b), and (c), respectively. A grid of weight ratios of isooctane in air is also shown. It is seen in figure 7 that the flammable region (rich limit minus lean limit) broadens up to an ammonia-air ratio of approximately 0.02, but begins to diminish beyond this point. The lean limit increases very slightly as

ammonia is added. This increase might be expected, since the lean-limit equivalence ratio for pure ammonia is larger than that of isooctane. On the other hand, the rich-limit equivalence ratio maximizes at an ammonia-air ratio of about 0.02, although the rich-limit equivalence ratio of ammonia is much smaller than that of isooctane. Thus for ammonia-air ratios of 0.020, rich-limit equivalence ratios were 10 to 20 percent higher than values for isooctane alone.

The limits for the ternary mixtures can be considered together with the prediction of Le Chatelier's mixture rule (ref. 6). Le Chatelier proposed a simple additive formula to connect the lower limit of a mixture of combustibles with the lower limits of the pure fuels. It may be stated mathematically as $\frac{n_1}{N_1} + \frac{n_2}{N_2} = 1$; where N_1 and N_2 are the lean limits of each gas separately in air, and n_1 and n_2 are the percentages by volume of the two gases in any lean-limit mixture of the two in air. The rule may also be applied to rich limits, if N_1 , N_2 , n_1 , and n_2 are defined at the rich limit. A modified form of the rule enables one to calculate the limits of any mixture of two or more combustible gases (ref. 11). The transformed equation is

$$L = \frac{100}{\frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + \dots} \quad (4)$$

where L is the limit of the mixture of combustible gases, and P_1 , P_2 , and so forth, are the proportions in percent of each combustible gas present in the original mixture, free from air and inert gases; N_1 , N_2 , and N_3 are the limits of each gas separately in air.

From the modified equation, rich and lean limits were calculated for the ternary mixtures at 60°, 210°, and 395° C; the results are plotted in figure 7. At the lean limit for every temperature, agreement between the experimental and calculated values is good. At the rich limit, however, the mixture rule predicts a regular decrease in the limit as ammonia-air ratio is increased, and it is seen that the experimental limits increase, then decrease, indicating an optimum ammonia-air ratio for promoting the burning of isooctane in air. It is not surprising that the calculated rich limit does not agree with the experimental curve because the greater discrepancies have been found with upward propagating flames, especially when one of the constituents is capable of propagating cool flames (ref. 12). This may account for the discrepancy observed here, for the flames were propagated upward and isooctane is known to be capable of cool-flame propagation (ref. 13), at least at higher temperatures.

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The effect of ammonia-air ratio on the minimum pressure at constant temperature can be examined by considering data of figures 2 to 5. While the data are somewhat uncertain, they suggest that for small additions of ammonia (up to ammonia-air ratios of perhaps 0.02) the minimum pressure decreases somewhat, at least at the higher temperatures. An optimum concentration of ammonia is again indicated, as was seen at the rich limit (fig. 7), for increasing the flammable region of isooctane. Since the minimum pressure limit is extremely high for ammonia (162 mm at 60° C and 140 mm at 335° C), it appears that the additive inhibits burning at low pressures when the ammonia-air ratio exceeds approximately 0.02. For ammonia in air (fig. 3), minimum pressures occurred at an equivalence ratio less than 1; whereas, for isooctane (fig. 2) and isooctane-ammonia-air mixtures (figs. 4 and 5), minimum pressures were found on the rich side. A similar trend has been observed in the case of maximum burning velocities. For ammonia, maximums occur on the lean side (ref. 14), whereas for hydrocarbons maximums are observed at equivalence ratios greater than 1.

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To estimate the extent of ammonia consumption, some gas-analysis data were obtained for rich and lean concentrations of the ternary mixtures. These data are recorded in table III, and the values in the "percent recovered" column for no ignition indicate the limited accuracy of the method. Roughly, the method was good to within ± 10 percent of the theoretical amount. The values given for ignited samples are based on those values for no ignition, and not on the theoretical amount, for example, 100 percent. Inspection of the table reveals that at lean equivalence ratios for both ternary mixtures (ammonia-air ratios of 0.020 and 0.039), no ammonia remained after passage of flame. On the other hand, at rich equivalence ratios approximately 38 to 52 percent of the ammonia was recovered for both mixtures indicating a consumption of about 48 to 62 percent. Since ammonia burns less readily than isooctane, it is somewhat surprising that any additive was consumed in the rich mixtures. Possibly the ammonia is thermally decomposed, or it may be absorbed by condensed water on the wall of the flame tube.

SUMMARY OF RESULTS

The pressure limits of flame propagation for isooctane, ammonia, and mixtures of the two in air were determined in a 2-inch-diameter tube closed at both ends. A hot wire was used as ignition source and propagation was upward. Variation of the propagation limits with the addition of ammonia and with temperature was investigated, and the following results were obtained:

1. All pressure-limit - equivalence-ratio curves showed two lobes except those curves for ammonia in air.

2. The flammable region (rich limit minus lean limit) widened when temperature was raised; the lean limit decreased uniformly but very little, while the rich limit was raised markedly.

3. The minimum pressure limit of flame propagation for all mixtures studied decreased when temperature was raised.

4. At 60° C, the flammable region of isooctane was found to be 3.6 times that of ammonia in terms of equivalence ratio.

5. On addition of ammonia, the flammable region of isooctane increased at first, but then decreased as the ammonia-air ratio exceeded 0.02.

6. The lean limit of isooctane increased very little but linearly as the ammonia-air ratio was increased.

7. Limits calculated from the mixture rule of Le Chatelier show the lean limits in good agreement with experimental values, but wide differences appeared at the rich limits.

8. Gas-analysis data for ammonia showed that all the additive was consumed on the passage of flame in lean mixtures; and approximately 48 to 62 percent was used in the rich mixtures.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 9, 1955

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TABLE I. - PRESSURE LIMITS OF FLAME PROPAGATION FOR ISOOCTANE IN
AIR AND AMMONIA IN AIR AT VARIOUS TEMPERATURES

(a) Isooctane in air

Flame-tube temperature, °C									
60		145		210		323		395	
Equiva- lence ratio	Pres- sure limit, mm Hg	Equiva- lence ratio	Pres- sure limit, mm Hg	Equiva- lence ratio	Pres- sure limit, mm Hg	Equiva- lence ratio	Pres- sure limit, mm Hg	Equiva- lence ratio	Pres- sure limit, mm Hg
4.61	>400	4.23	>400	4.30	>400	4.60	>400	4.30	>400
4.08	>400	3.61	>400	3.88	314	4.20	335	3.96	294
3.50	200	3.43	222	3.71	300	3.94	318	3.78	296
2.92	108	3.30	164	3.48	280	3.73	312	3.64	284
2.45	94	2.77	97	3.32	170	3.58	310	3.38	232
2.19	88	2.10	114	2.60	105	3.13	257	2.85	103
1.80	98	1.73	76	1.97	54	2.54	122	2.14	46
1.59	56	1.27	37	1.25	39	1.91	55	1.63	28
1.15	44	.89	44	.86	42	1.20	37	1.04	33
.78	57	.58	70	.57	74	.70	43	.65	46
.56	119	.49	114	.47	122	.48	69	.38	110
----	---	.42	>400	.42	230	.37	140	.30	>400

(b) Ammonia in air

Flame-tube temperature, °C			
62		335	
Equiva- lence ratio	Pres- sure limit, mm Hg	Equiva- lence ratio	Pres- sure limit, mm Hg
1.55	>400	1.83	340
1.47	345	1.66	274
1.25	208	1.45	227
1.02	167	1.19	176
.90	161	1.01	155
.89	162	.91	144
.80	162	.75	144
.72	164	.59	156
.67	179	.49	198
.61	236	.46	245
.54	>400	.44	>400

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TABLE II. - PRESSURE LIMITS OF FLAME PROPAGATION FOR ISOOCTANE-
AMMONIA-AIR MIXTURES

Ammonia-air ratio by weight					
0.020			0.039		
Equiva- lence ratio	Temper- ature, °C	Pressure limit, mm Hg	Equiva- lence ratio	Temper- ature, °C	Pressure limit, mm Hg
0.42 ↓ ↓	56 134 250 345 456	>400 >400 >400 >400 145	0.58 ↓ ↓	60 144 235 340 426	>400 >400 >400 168 151
0.59 ↓ ↓	100 142 252 343 446	>400 >400 134 76 64	0.71 ↓ ↓	71 145 238 340 454	234 178 113 98 87
0.65 ↓ ↓	66 152 252 354 442	~295 ~170 95 66 60	0.86 ↓ ↓	62 142 234 338 444	90 85 84 78 65
0.88 ↓ ↓	58 138 248 350 450	82 83 82 76 68	1.51 ↓ ↓	65 158 255 360 458	66 50 47 44 38
1.64 ↓ ↓	60 145 248 335 435	53 34 33 31 29	1.76 ↓ ↓	56 137 246 348 442	104 92 69 52 ~48
2.26 ↓ ↓	60 134 252 336 448	90 89 44 40 34	2.42 ↓ ↓	58 142 254 345 446	111 98 77 63 50

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TABLE II. - Concluded. PRESSURE LIMITS OF FLAME PROPAGATION
FOR ISOOCTANE-AMMONIA-AIR MIXTURES

Ammonia-air ratio by weight					
0.020			0.039		
Equiva- lence ratio	Temper- ature, °C	Pressure limit, mm Hg	Equiva- lence ratio	Temper- ature, °C	Pressure limit, mm Hg
3.00 ↓ ↓	58 146 246 335	105 106 94 74	3.11 ↓ ↓	74 160 258 368	133 140 182 210
3.70 ↓ ↓	62 132 244 335 445	205 180 224 ~320 235	3.33 ↓ ↓	445 69 150 238 340	~260 160 212 207 298
4.09 ↓ ↓	63 140 238 325 435	279 245 ~280 320 266	3.64 ↓ ↓	452 65 144 232 335 444	297 244 275 225 257 ~380
4.18 ↓ ↓	62 136 245 335 439	>400 274 290 ~325 287	3.96 ↓ ↓	57 145 251 351 468	>400 >400 >400 >400 ~231
4.48 ↓ ↓	55 135 245 362 452	>400 >400 321 327 259			
4.82 ↓ ↓	--- --- 252 357 460	--- --- ~378 ~336 ~244			

TABLE III. - GAS-ANALYSIS DATA FOR AMMONIA

IN ISO-OCTANE-AMMONIA-AIR MIXTURES

Ammonia-air ratio by weight							
0.020				0.039			
Equiva- lence ratio	Ignition	Recovered, percent	Temper- ature, °C	Equiva- lence ratio	Ignition	Recovered, percent	Temper- ature, °C
0.79	no	90.3	58	1.04	no	109.0	70
↓	yes	0.0	↓	↓	no	103.0	↓
↓	yes	0.0	↓	↓	yes	0.0	↓
↓	no	91.2	338	↓	yes	0.0	↓
↓	yes	0.0	↓	3.58	no	89.1	68
↓	yes	0.0	↓	↓	no	106.0	↓
3.73	no	88.5	66	↓	yes	51.9	↓
↓	yes	39.4	↓	↓	yes	39.8	↓
↓	yes	40.0	↓				
↓	no	90.9	345				
↓	yes	38.9	↓				
↓	yes	38.9	↓				

3598

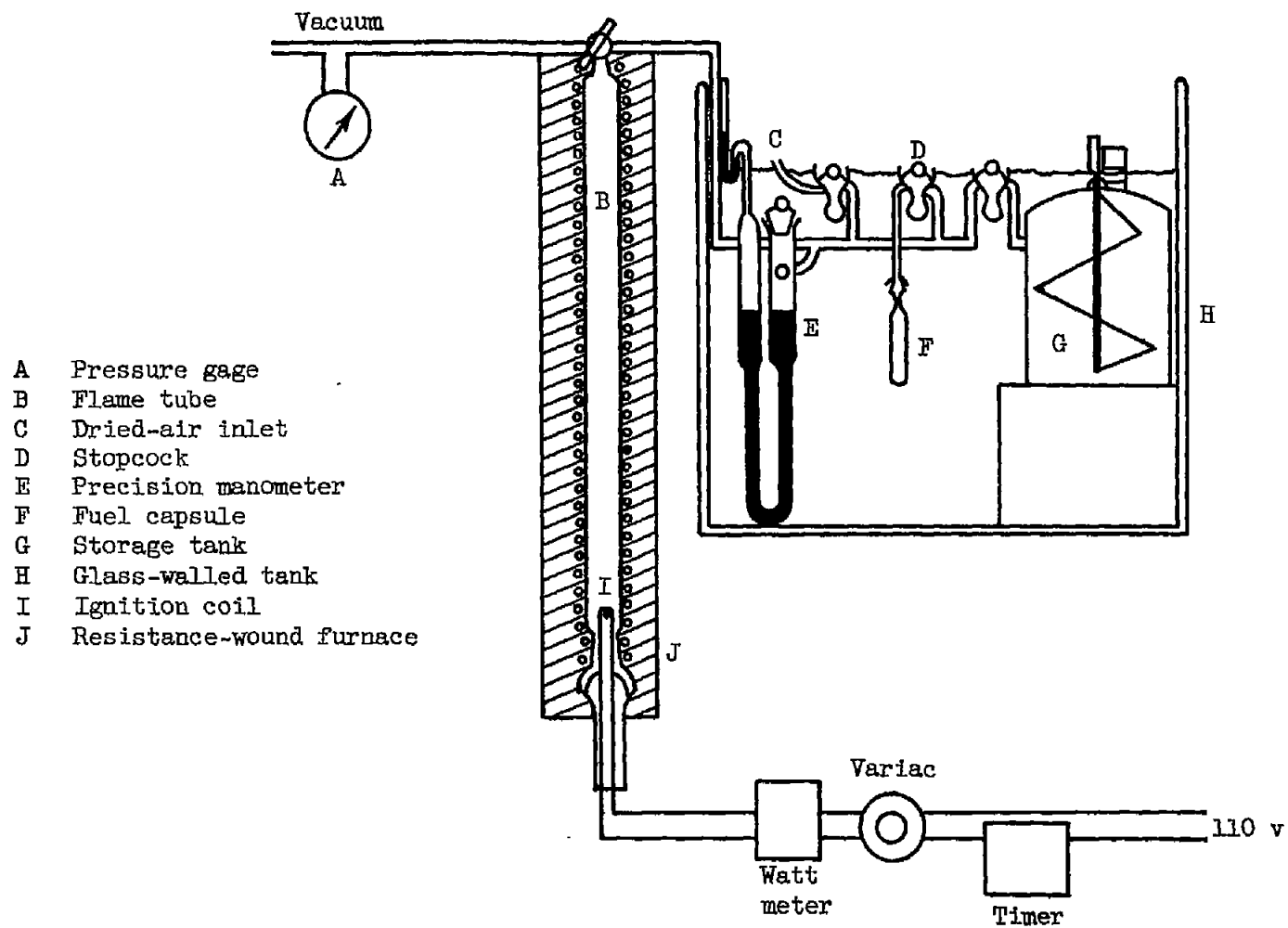


Figure 1. - Apparatus for determining pressure limits.

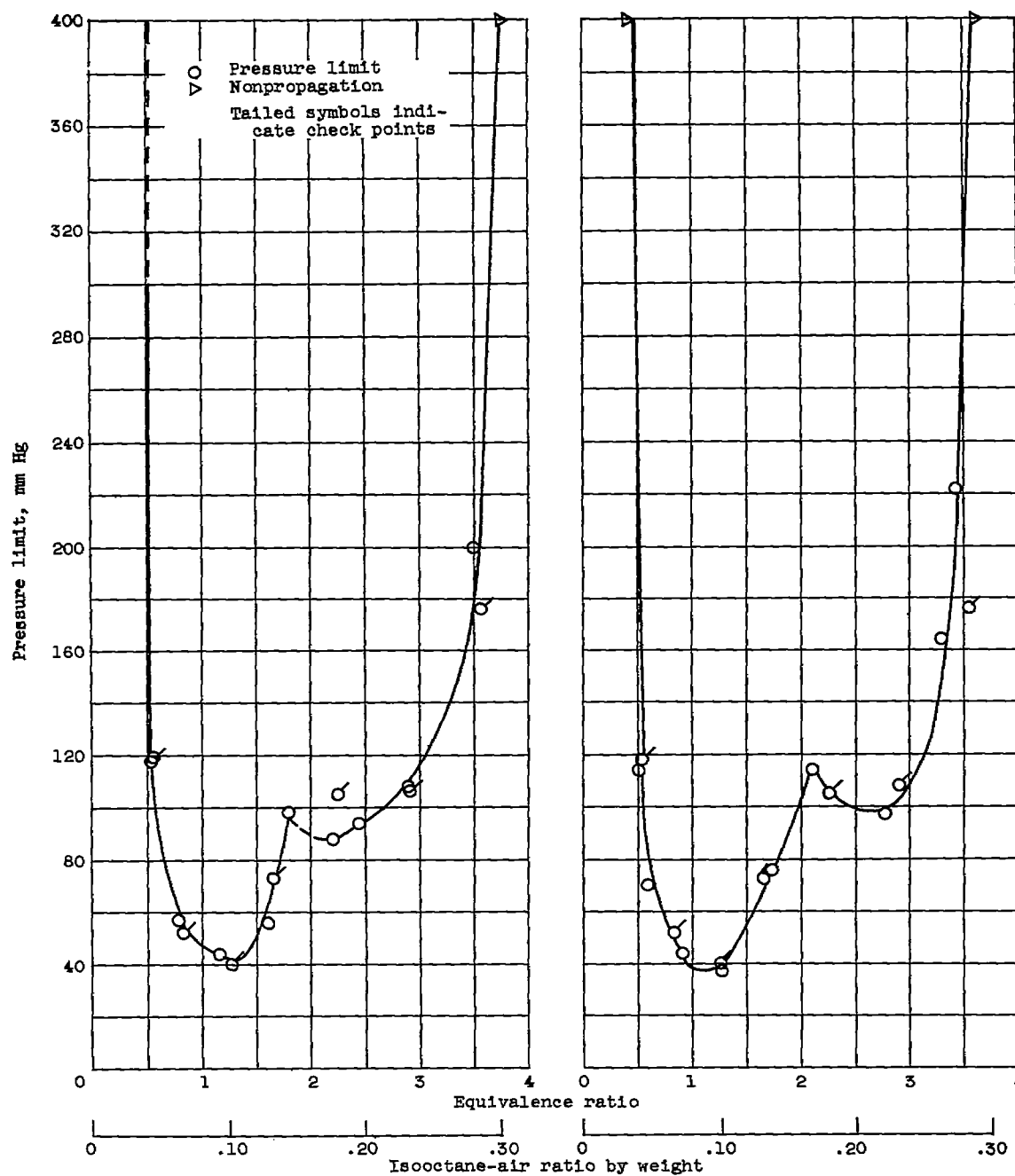


Figure 2. - Limits of flame propagation for isooctane in air.

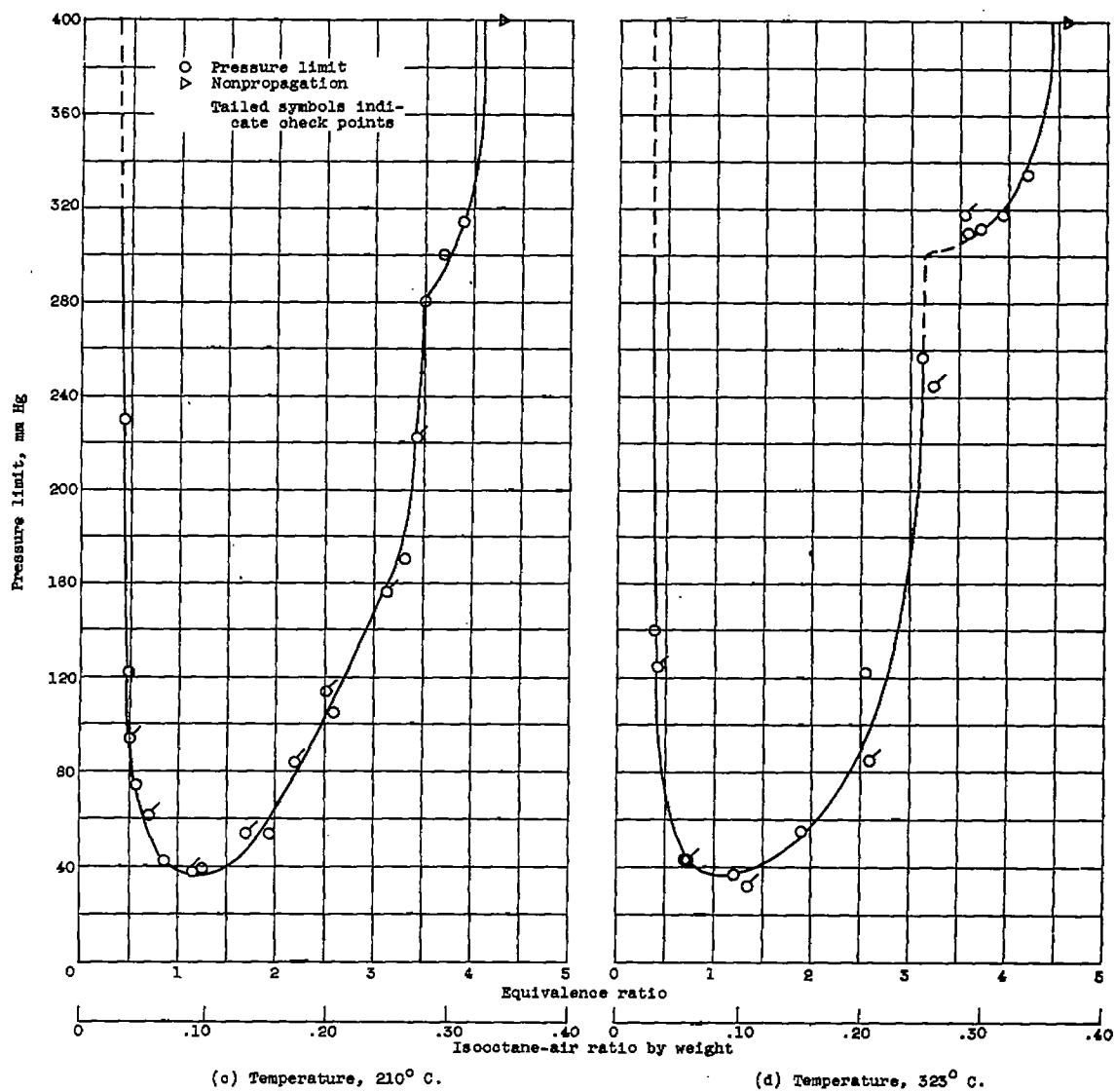
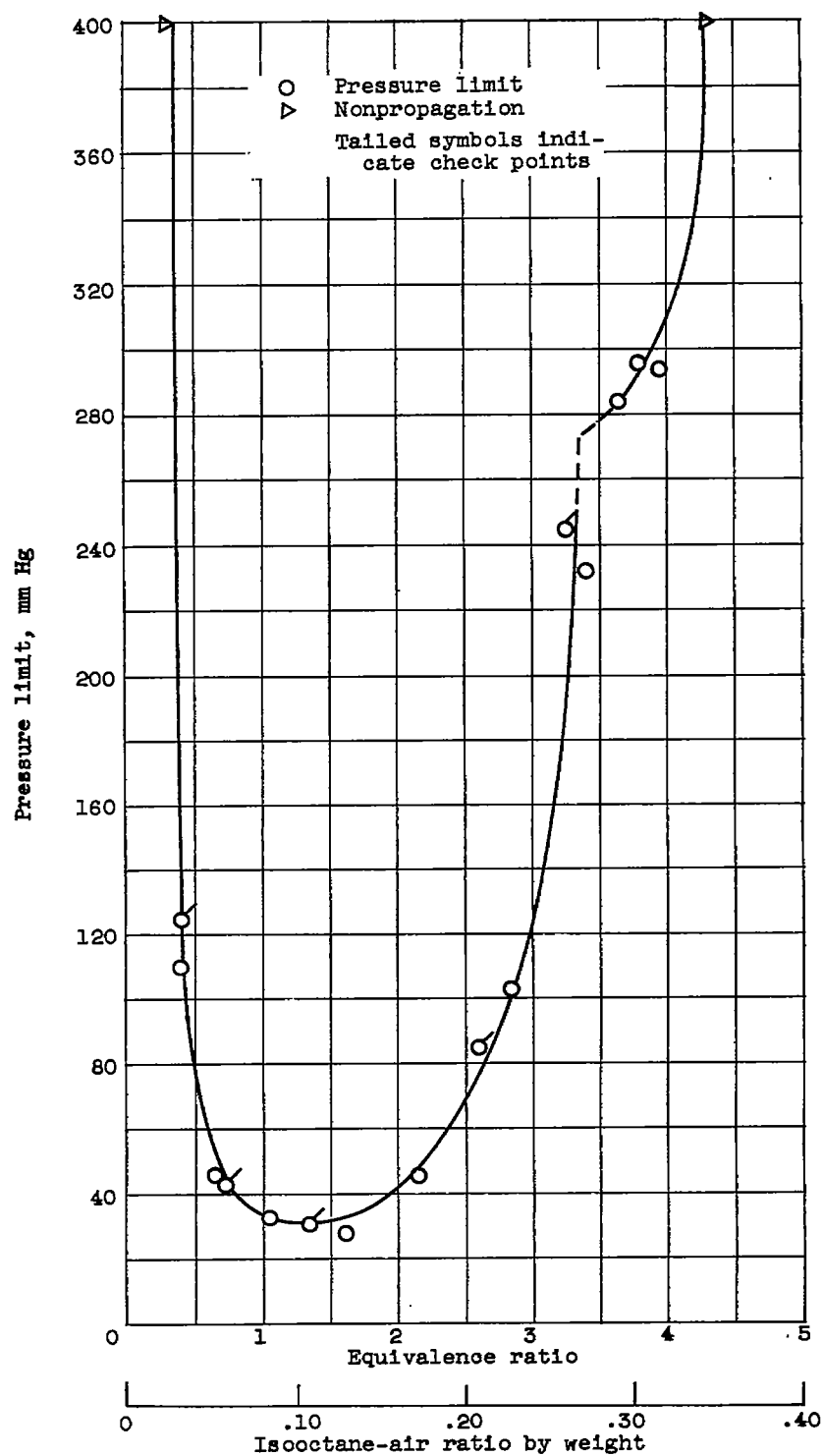
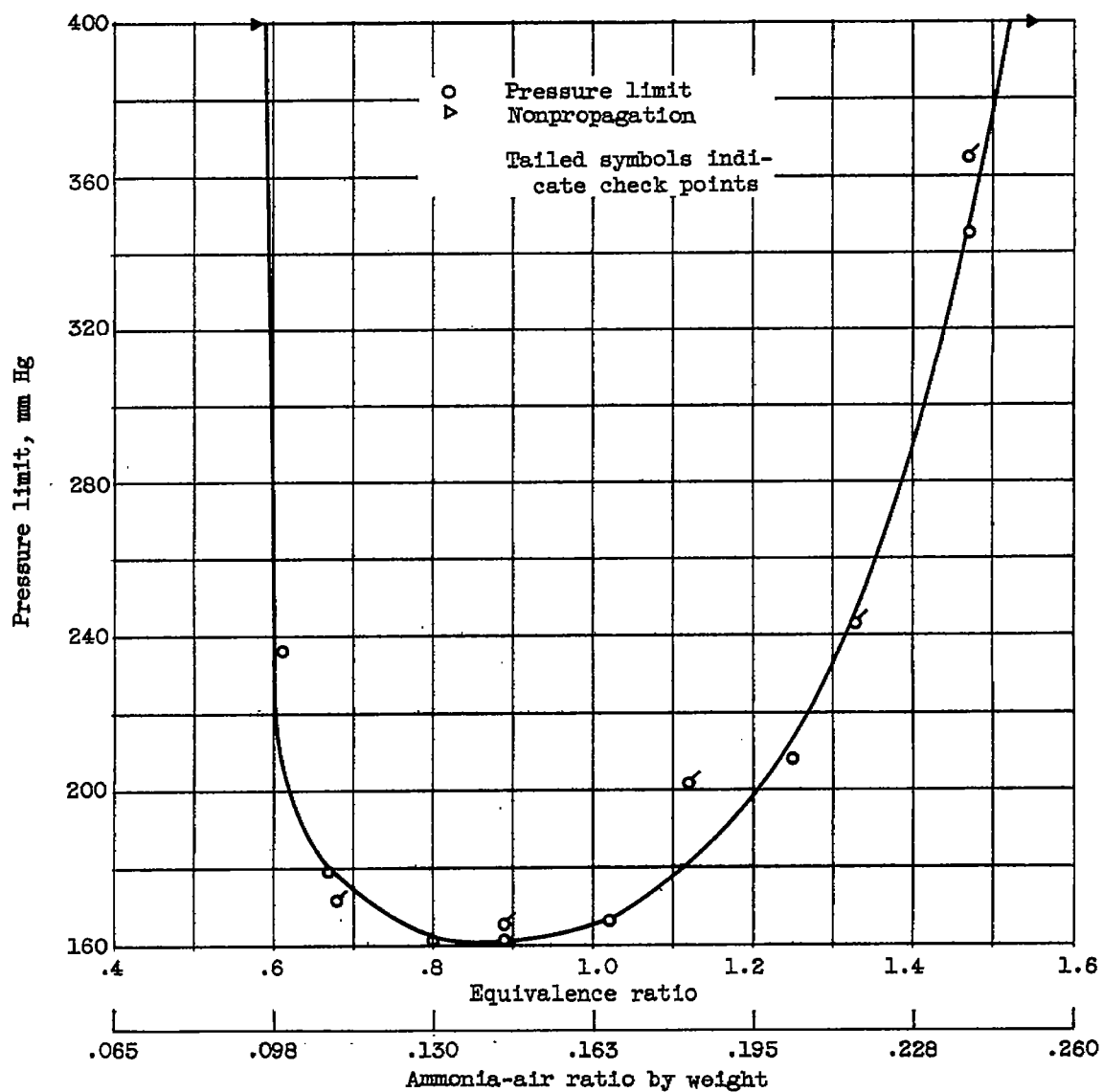


Figure 2. - Continued. Limits of flame propagation for isooctane in air.



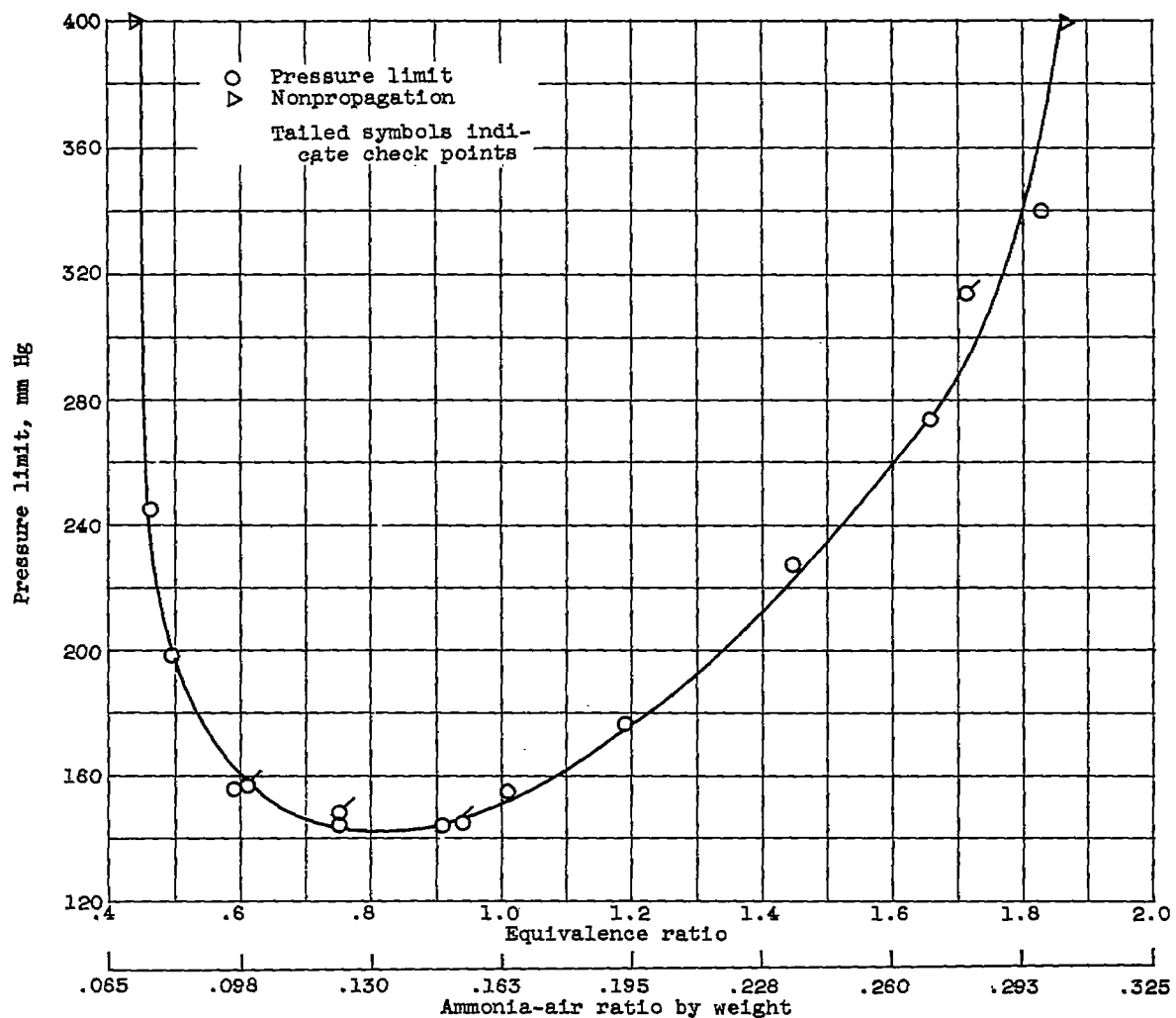
(e) Temperature, 395° C.

Figure 2. - Concluded. Limits of flame propagation for isooctane in air.



(a) Temperature, 62° C.

Figure 3. - Limits of flame propagation for ammonia in air.



(b) Temperature, 335° C.

Figure 3. - Concluded. Limits of flame propagation for ammonia in air.

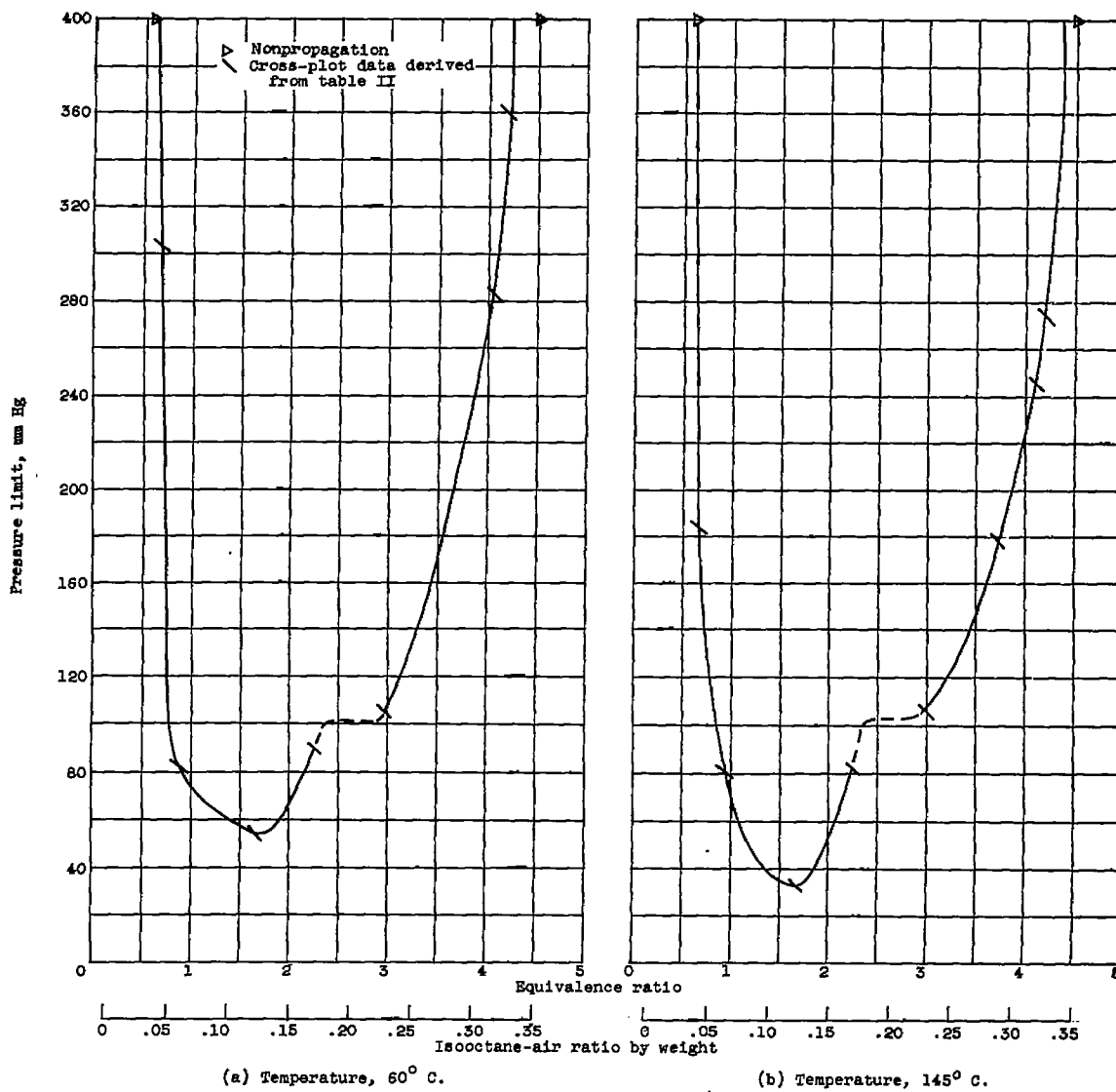
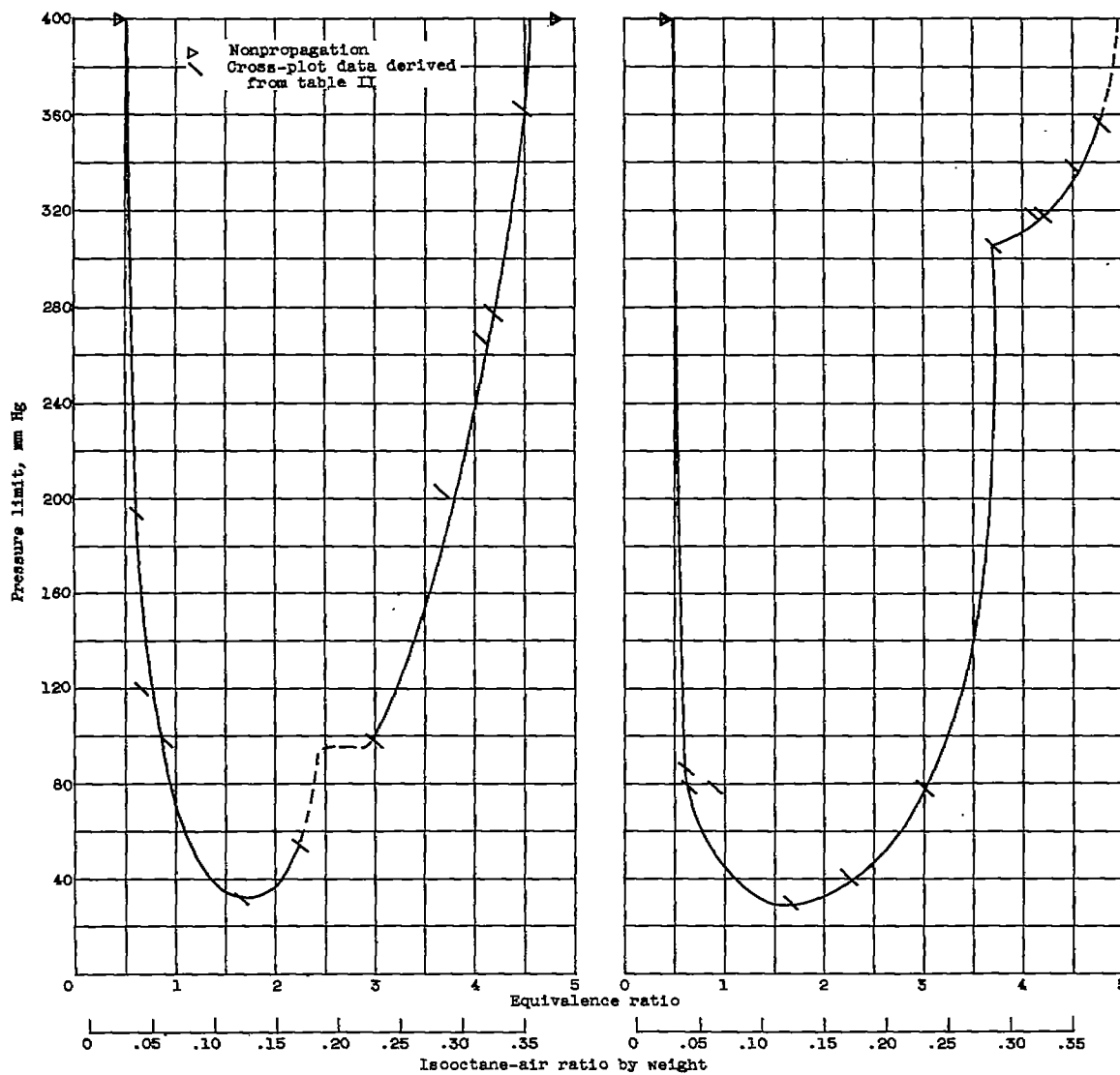
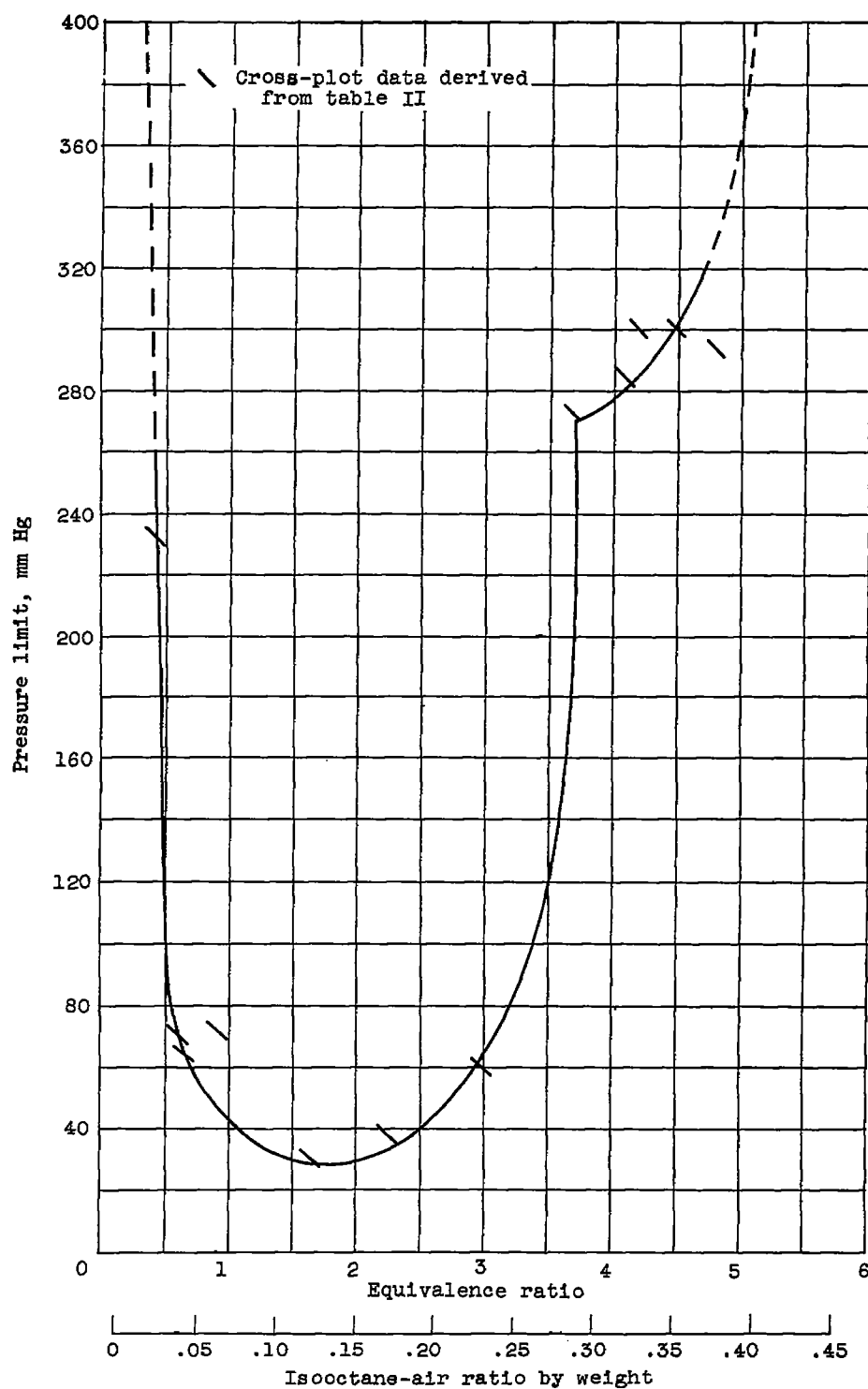


Figure 4. - Limits of flame propagation for ternary mixtures at ammonia-air ratio of 0.020.





(e) Temperature, 395° C.

Figure 4. - Concluded. Limits of flame propagation for ternary mixtures at ammonia-air ratio of 0.020.

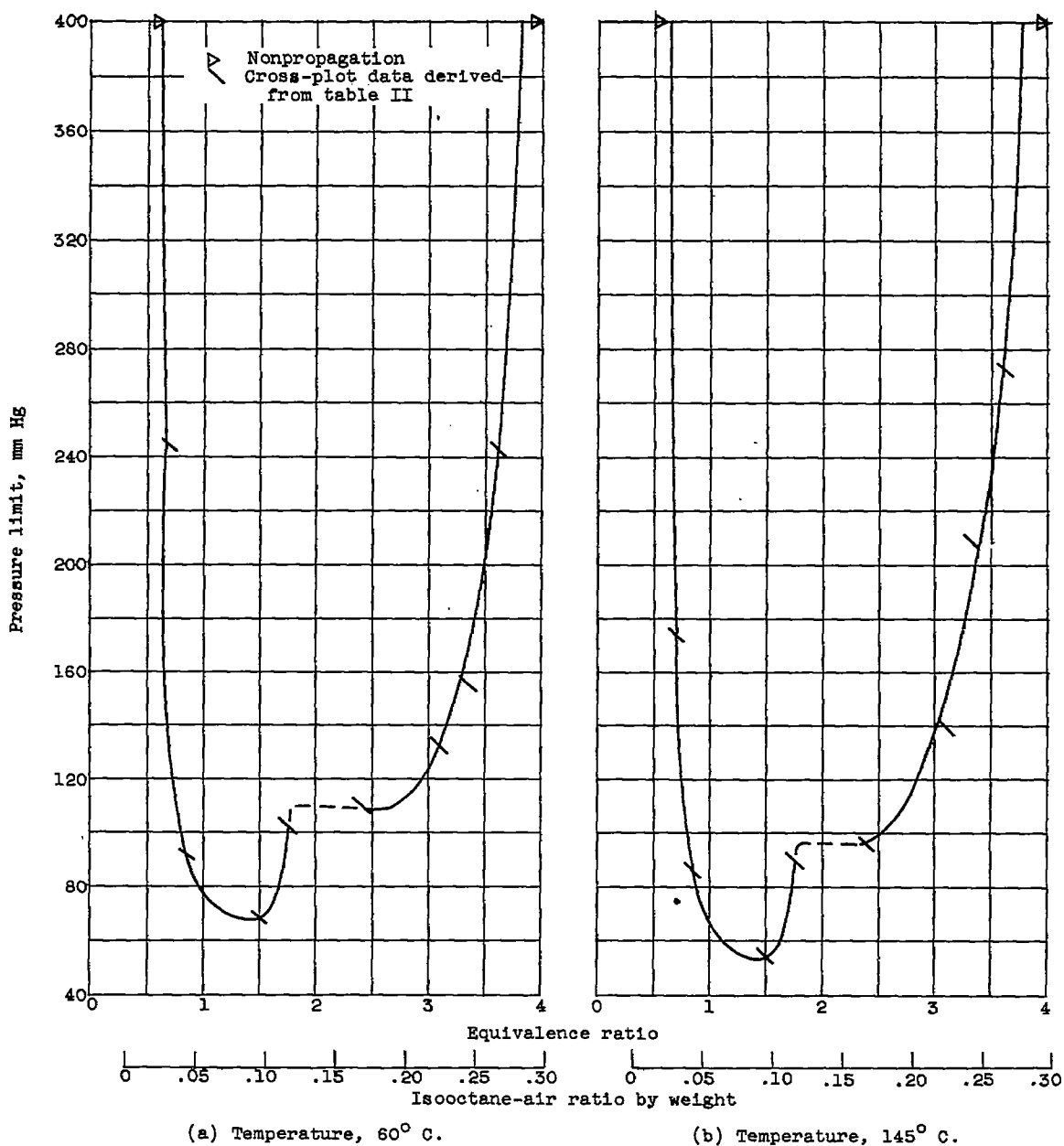
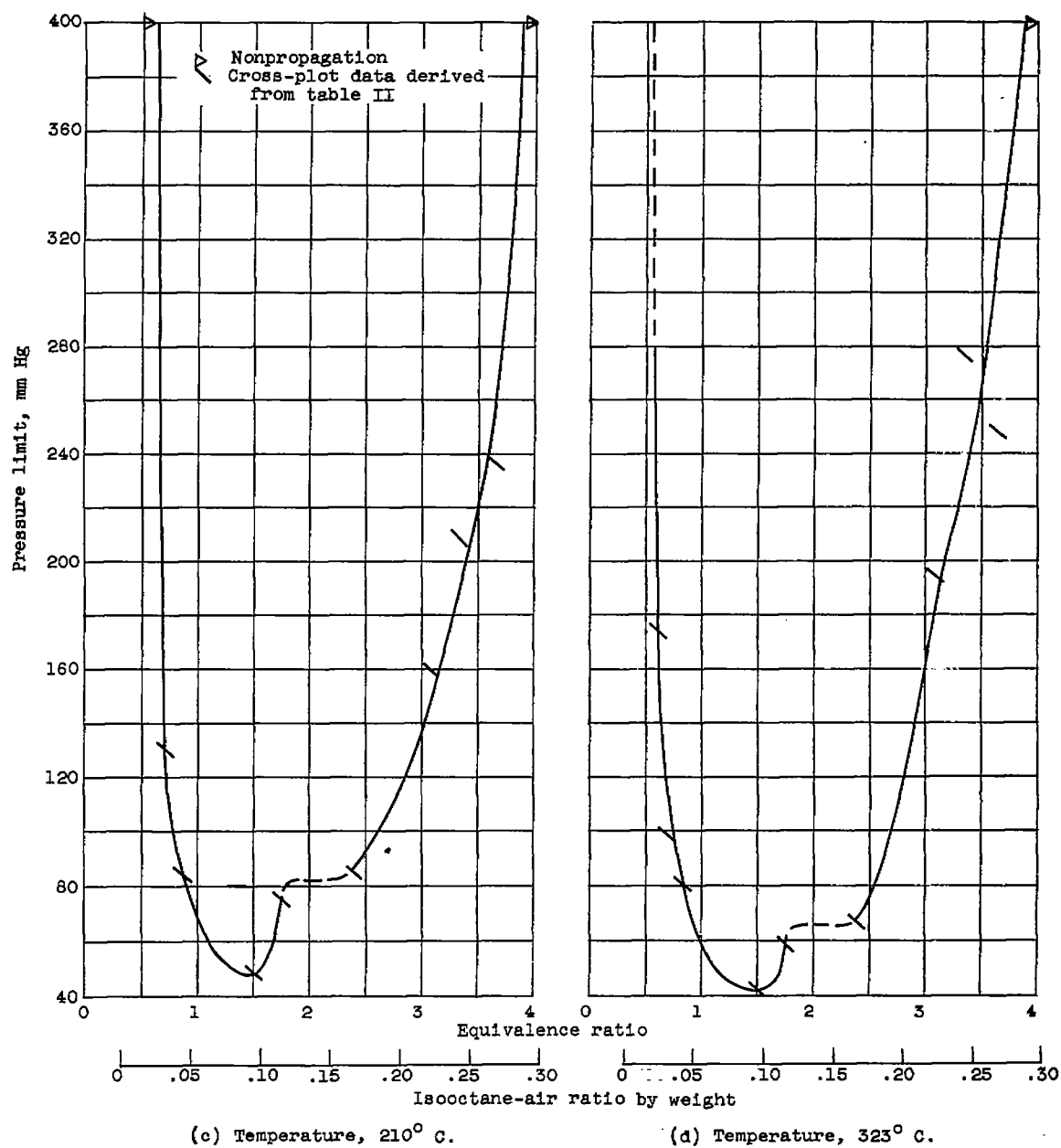
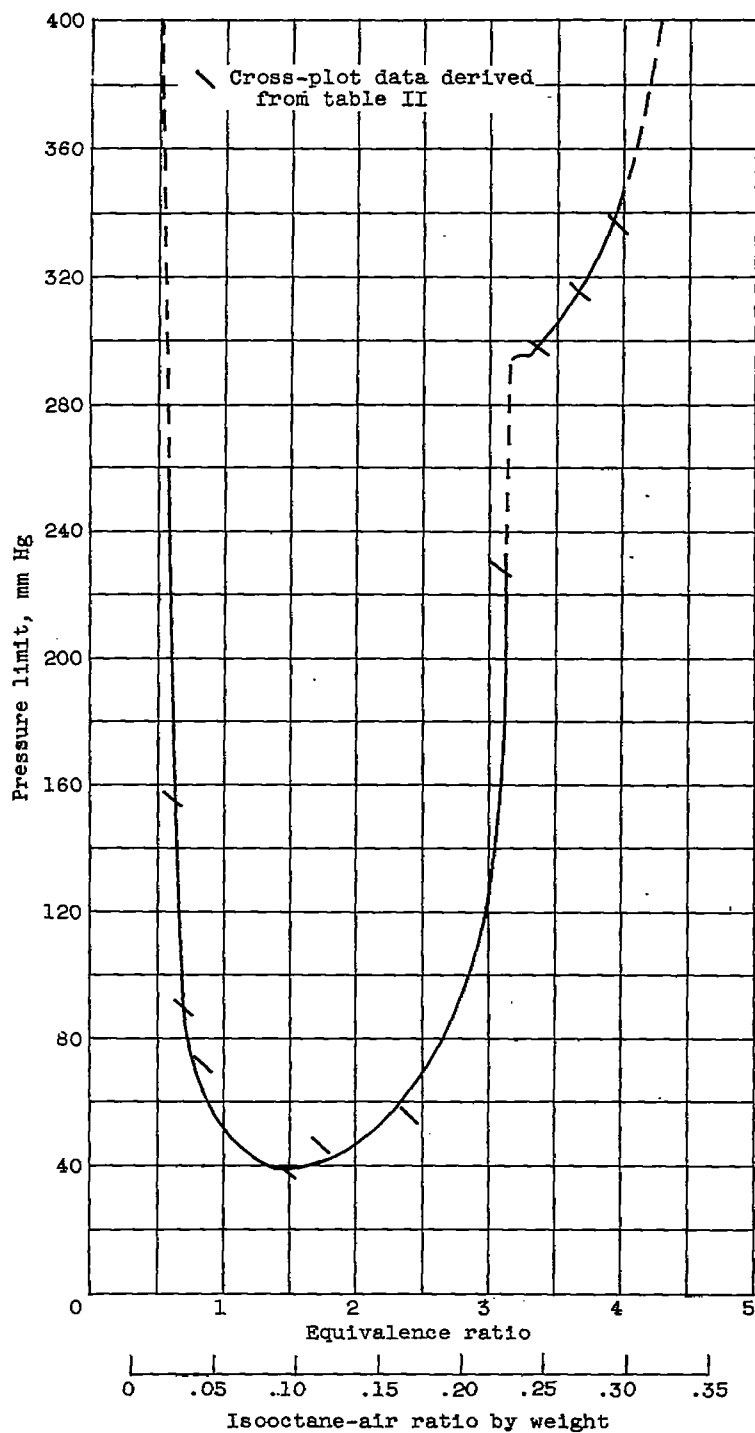


Figure 5. - Limits of flame propagation for ternary mixtures at ammonia-air ratio of 0.039.





(e) Temperature, 395° C.

Figure 5. - Concluded. Limits of flame propagation for ternary mixtures at ammonia-air ratio of 0.039.

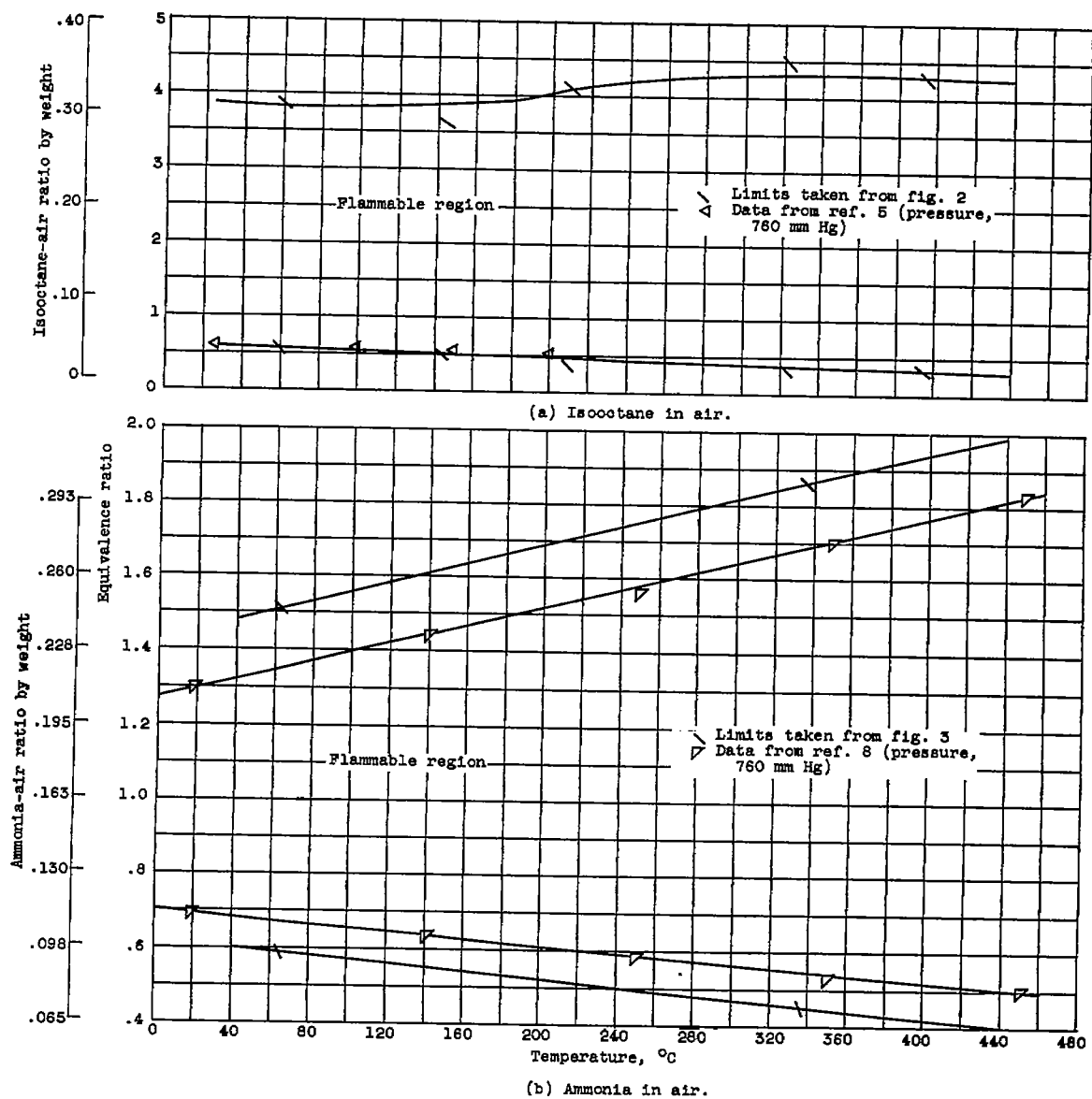


Figure 6. - Effect of temperature on limits of flame propagation. Pressure, 400 millimeters of mercury.

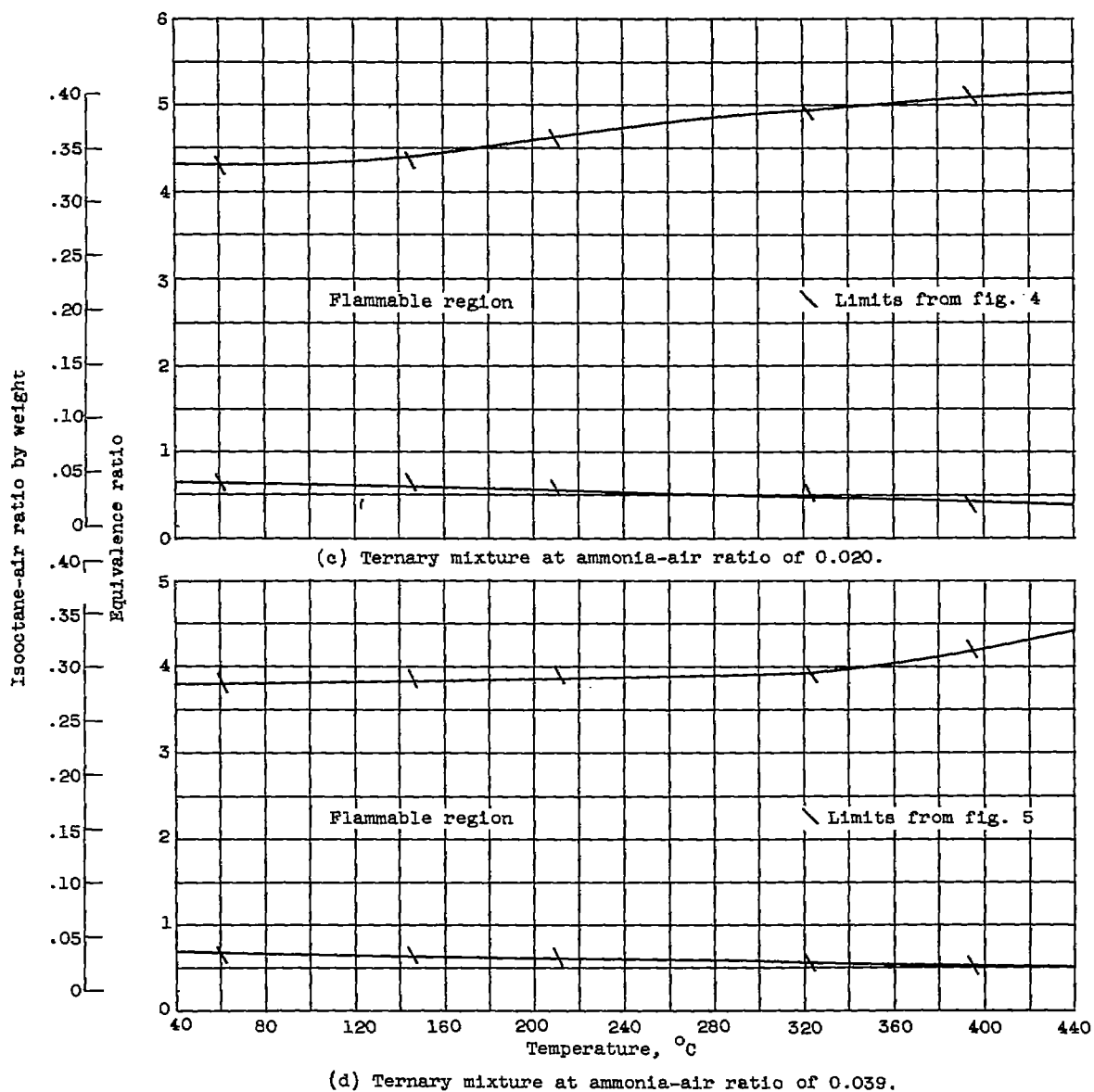
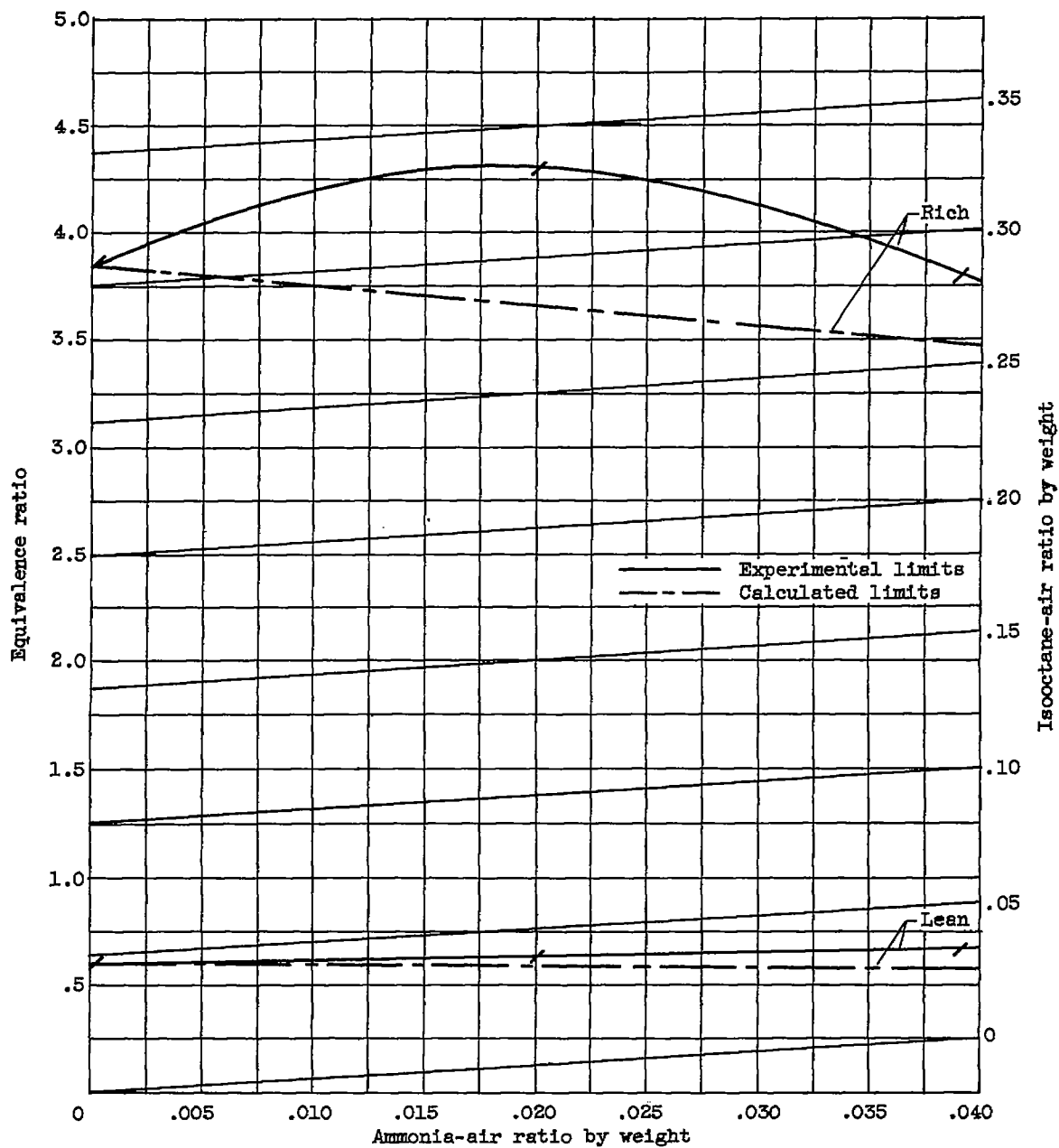
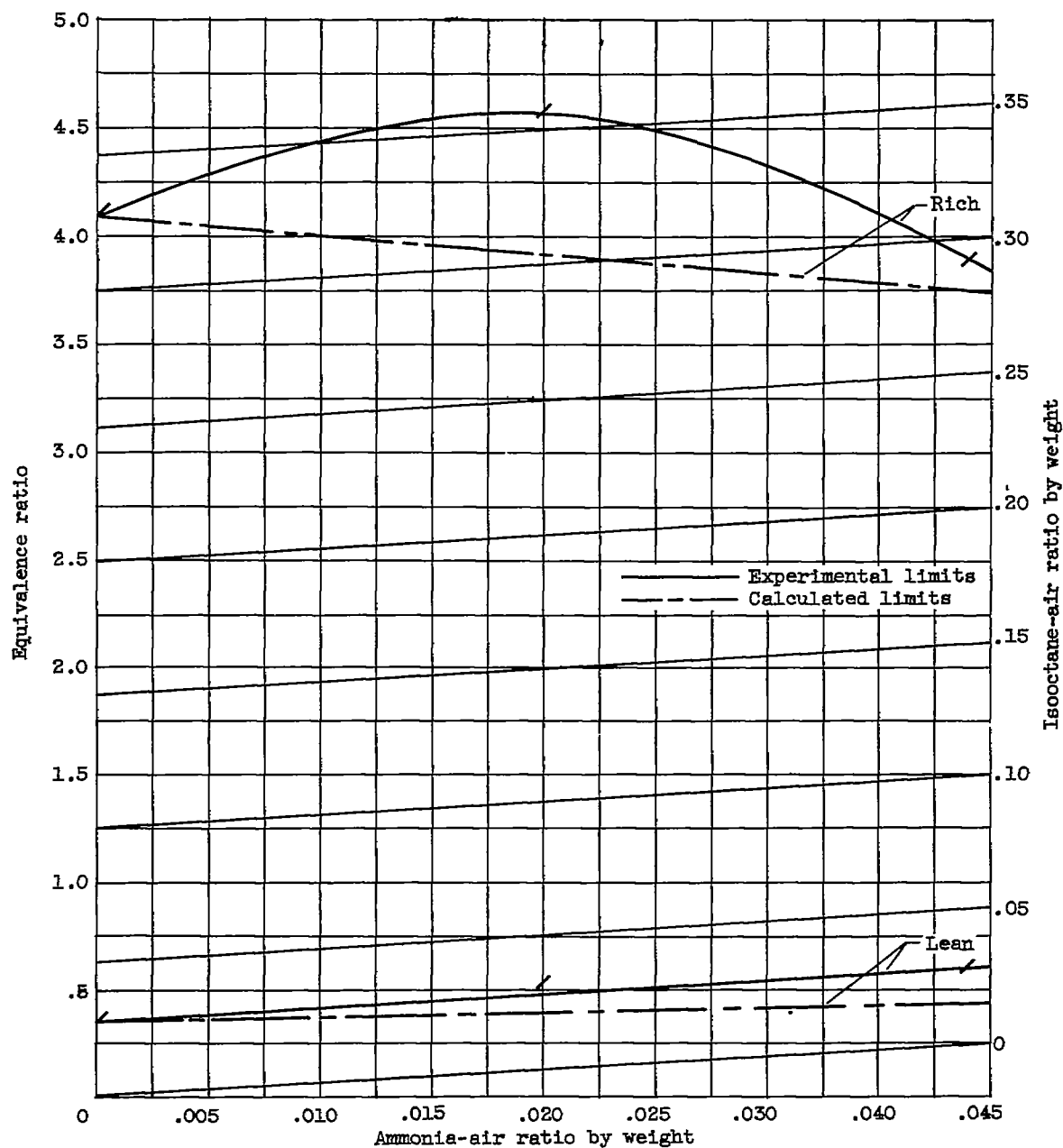


Figure 6. - Concluded. Effect of temperature on limits of flame propagation.
Pressure, 400 millimeters of mercury.



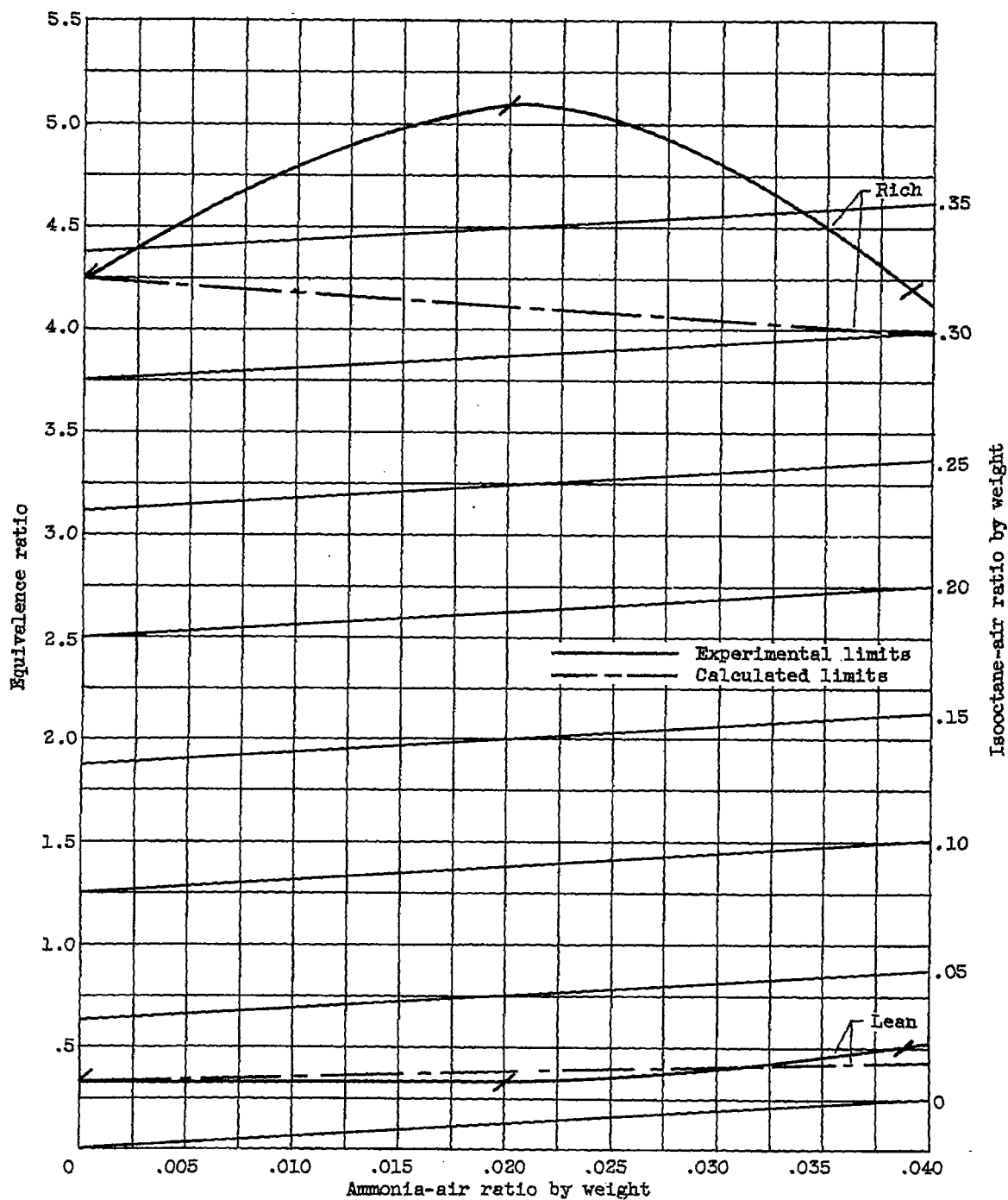
(a) Temperature, 60° C. Limits taken from figures 2(a), 4(a), and 5(a).

Figure 7. - Effect of ammonia-air ratio on limits of flame propagation of ternary mixtures. Pressure, 400 millimeters of mercury.



(b) Temperature, 210° C. Limits taken from figures 2(c), 4(c), and 5(c).

Figure 7. - Continued. Effect of ammonia-air ratio on limits of flame propagation of ternary mixtures. Pressure, 400 millimeters of mercury.



(c) Temperature, 395° C. Limits taken from figures 2(e), 4(e), and 5(e).

Figure 7. - Concluded. Effect of ammonia-air ratio on limits of flame propagation of ternary mixtures. Pressure, 400 millimeters of mercury.